Gravity and Geological Studies of an Ultramafic Mass in New Zealand[1]

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ABSTRACT: A gravity and geologic survey was carried out over a portion of the Nelson ultramafic belt of the South Island. In this region, the ultramafic rocks outcrop over a 5-mile-wide belt and abut against the Alpine greywacke along the right lateral transcurrent Alpine Fault. The dunite and peridotite of the ultramafic belt as well as the overlying geosynclinal sediments strike north. At their southern extremity, these rocks are faulted by the northeast–southwest striking Alpine Fault against the massive Alpine greywackes to the south of the fault. There is a complete discordance of the stratigraphic elements between the two sides of the fault. The basal Permian ultramafic belt (Wairau ultramafic mass) to the north of the fault is horizontally layered and shows inch-scale layering comparable to that observed by Hess in the Stillwater complex of Montana. Stratigraphically above the Wairau ultramafic mass and also on the northern side of the fault lies a vertically dipping, 31,000-ft-thick sequence of serpentinite, spilite, grey slate, red and green slate, and tuffaceous sandstone. The density of the rocks surrounding the Wairau ultramafic mass varies between 2.65 gm/cc and 2.75 gm/cc, while that of the peridotite and dunite varies between 3.2 gm/cc and 3.3 gm/cc. A total thickness of 7,000 ft for the Wairau ultramafic mass was computed, using the average density contrast of 0.5 gm/cc between the ultramafics and the country rock. Gravity analysis also shows that the Alpine Fault dips 67° southeast along the contact between the ultramafics and the Alpine greywacke.

It is thought that the Wairau ultramafic mass was emplaced as a vertical dike when the surrounding rocks were horizontal and that the dike and the surrounding rocks have been rotated by 90° so that the dike is now horizontal and the beds are vertical. Comparisons between the stratigraphic sequence studied here and an almost identical sequence on the southern side of the Alpine Fault in Otago province supports the previously postulated 300-mile-long transcurrent displacement between the two areas along the Alpine Fault system of New Zealand. Studies of displacement of post-glacial river terraces along the Alpine Fault in Nelson show an average right lateral movement of 0.36 inches per year along the fault since the last glaciation.

THE ORIGIN of emplacement of ultramafic rocks has always been a prime geologic problem in world geology. There are two ultramafic belts in New Zealand and these are separated by a 300-mile-long displacement along the Alpine Fault system of New Zealand. The New Zealand ultramafic belts have an added interest because of this prominent fault movement. They provide an accessible source for geophysical and geological investigation, in the country where dunite was first described.

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Of particular interest to the geophysicist and geologist alike are the two areas where the ultramafic rocks abut against the fault planes of the Alpine Fault. In these regions, a genuine physical cross section is obtained across the ultramafic rocks and their associated formations where the Alpine Fault system has cut across the formations.

One of these two regions is located in South Nelson in the northern part of the South Island of New Zealand and has been named, in this paper, the Tophouse district. A reconnaissance geological survey was carried out by the author in 1961–1962 over the Tophouse district in order to map the geologic boundaries of the ultramafic belt and all visible fault traces of the Alpine Fault system. Another purpose of the geological survey was to compare the lithology, structure, and thickness of the geologic formations in the Tophouse district immediately north of the Wairau Fault with similar formations south of the Alpine Fault in Otago, 300 miles southwest of the Tophouse district.

A gravity survey was carried out simultaneously with the geological survey over the Tophouse district in order to map the maximum thickness of the ultramafic rocks, and their attitude as they abut against the Wairau Fault, and to investigate whether there is any subsurface extension of the ultramafic belt south of the fault in the Tophouse district. Gravity surveying appears to be one of the best geophysical methods to use in the study of ultramafic belts because of the high density contrast usually measured between the peridotite and the country rock into which the peridotite has been intruded.

It is hoped that this paper will serve as a useful contribution to the gravimetric study of ultramafic rocks throughout the world.

GEOLOGY

Outline of Stratigraphy

The rocks of the Tophouse district (Fig. 1 and Table 1) consist of two classes, pre-Tertiary rocks and extensive post-glacial deposits. The pre-Tertiary rocks are divided into three fault blocks (Fig. 2): (1) the Brook Street volcanics west of the Waimea Fault and probably underlain by rocks of the Rotoroa igneous complex; (2) the Maitai and Te Anau series, east of the Waimea Fault and north of the Wairau Fault; and (3) the Alpine greywacke, south of the Wairau Fault.

The relationship between the rocks of the Tophouse district and those of the ultramafic belt in Otago south of the Alpine Fault is shown in Table 2.

Outline of Structure

The Wairau Fault, the major one of the district, is a right lateral fault downthrown to the north. It is probably a branch of the Alpine Fault, together with which it forms a 300-mile-long transcurrent fault system which separates the Maitai and Te Anau rocks of the Tophouse district from those of Otago (Wellman, 1956:25).

The strike of the Brook Street volcanics has changed as a result of stresses associated with movement along the Wairau Fault. At Tophouse, the Brook Street volcanics strike at 360°, i.e., parallel to the Waimea Fault. At Lake Rotoiti, these volcanics have been regionally bent to strike at 60° and fault swarms have developed at intermediate angles between the strike of the Waimea and Wairau faults. The Waimea Fault has not been active during the post-glacial period.

The Maitai and Te Anau formations have undergone strike-faulting, but the Wairau ultramafic mass shows little sign of structural deformation. Detailed geology of the Tophouse district is shown on the geological map, Figure 2, and the stratigraphic units are presented in Table 1.

Brook Street Volcanics

The Brook Street volcanics of the Te Anau series are part of the southern end of a sequence of Upper Paleozoic volcanics which extend from d'Urville Island to Tophouse. The continuous Waimea Fault between the Brook Street volcanics and the Maitai series makes stratigraphic relationship at Tophouse uncertain. No fossils were found in the Brook Street volcanics in the Tophouse district; however, they are considered Upper Paleozoic here, the age assigned by Bruce (1962:166) to the Brook Street volcanics of Nelson.

The bulk of the rocks are massive metasomatized spilites and green-grey keratophyres. Along the Waimea Fault, there is an outcrop of a green volcanic conglomerate. The spilites are dense, hard and nonvesicular. The dip of the volcanics has been determined from alignment of xenoliths and mineral grains. The spilite exposed in the Motupiko Valley is equigranular and fine grained, with 20% subcalcic augite ($2V = 20°$) and with 60% plagioclase feldspar. The augite crystals are corroded and set in a highly altered groundmass of epidote and chlorite. The green color of the Brook Street volcanics results from the alteration of mafic minerals to chlorite.

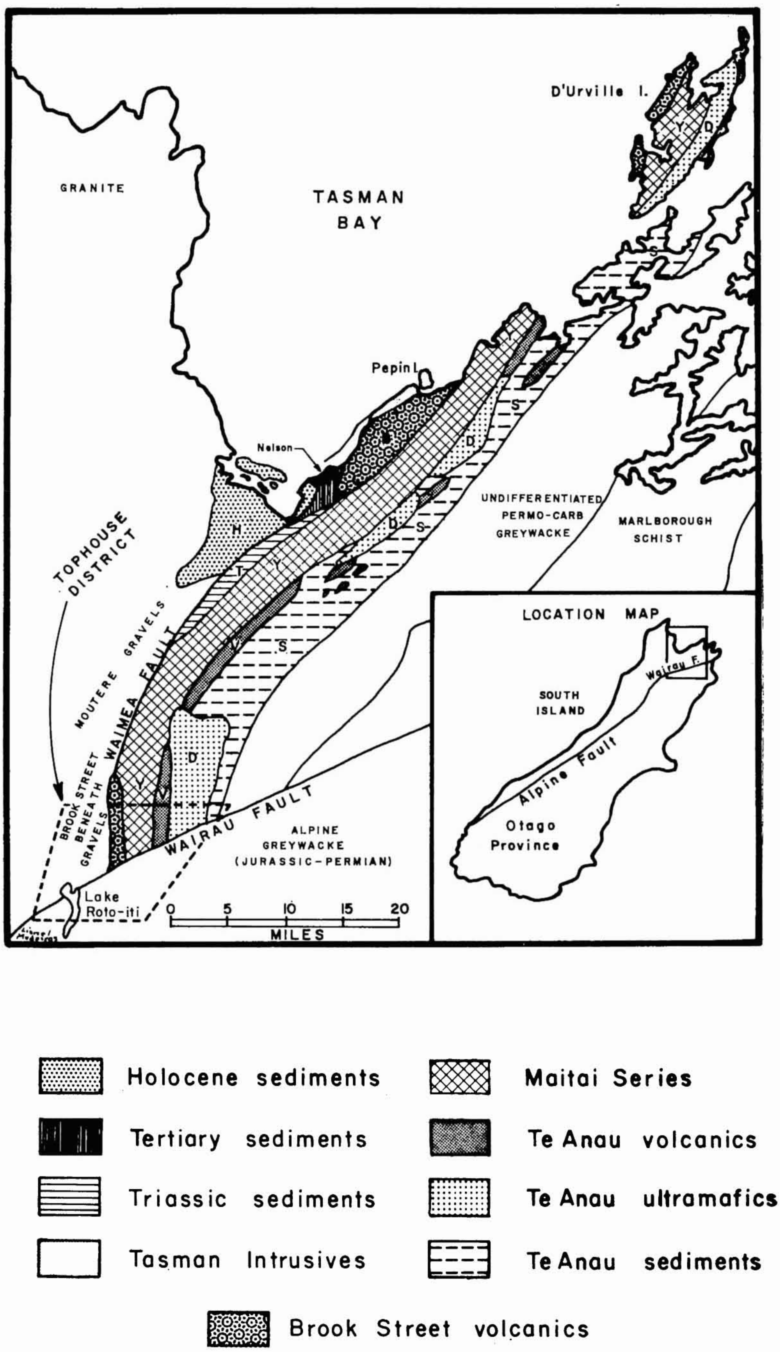


FIG. 1. Rock types north of the Tophouse district. Inset shows geographic location of Tophouse district.

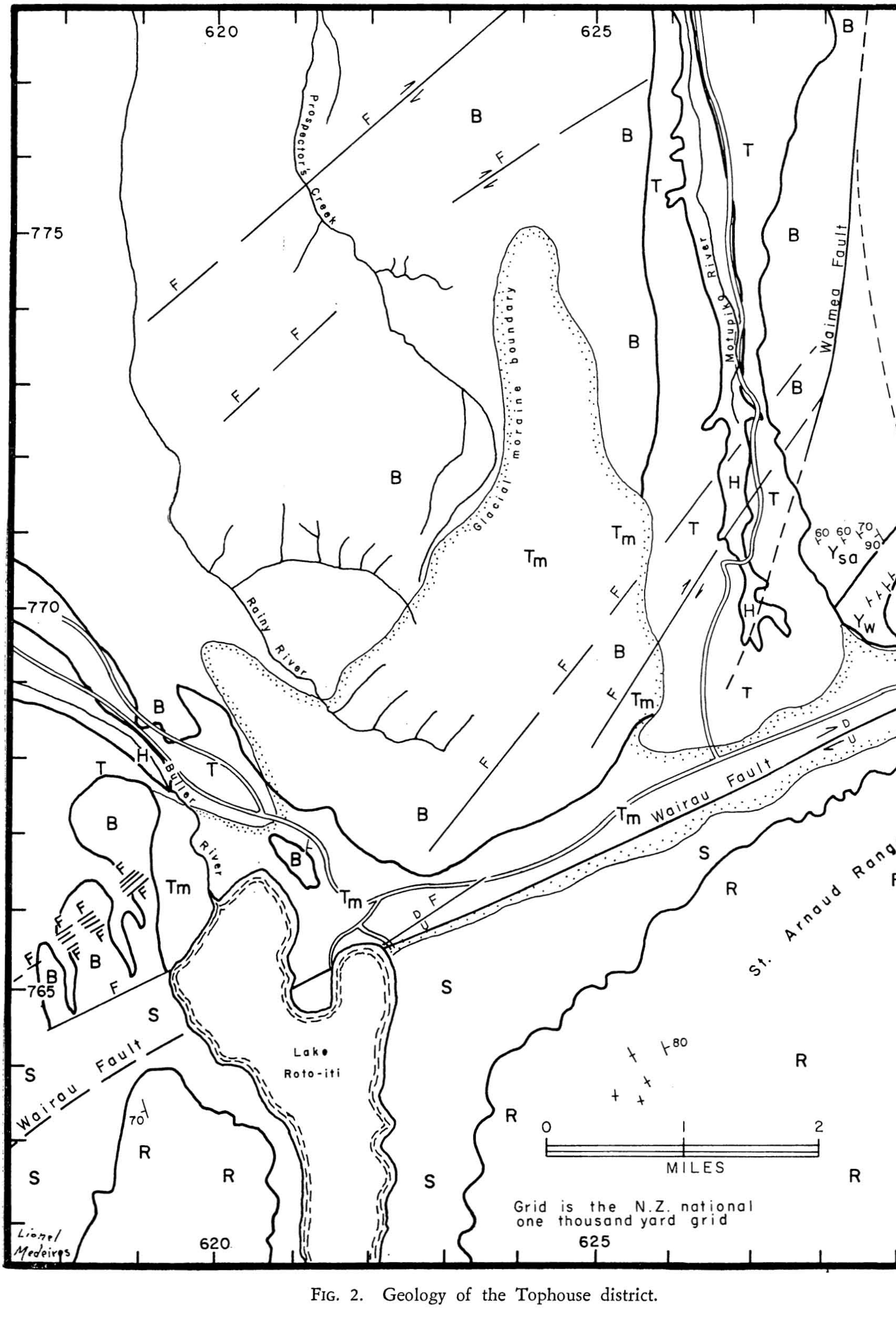
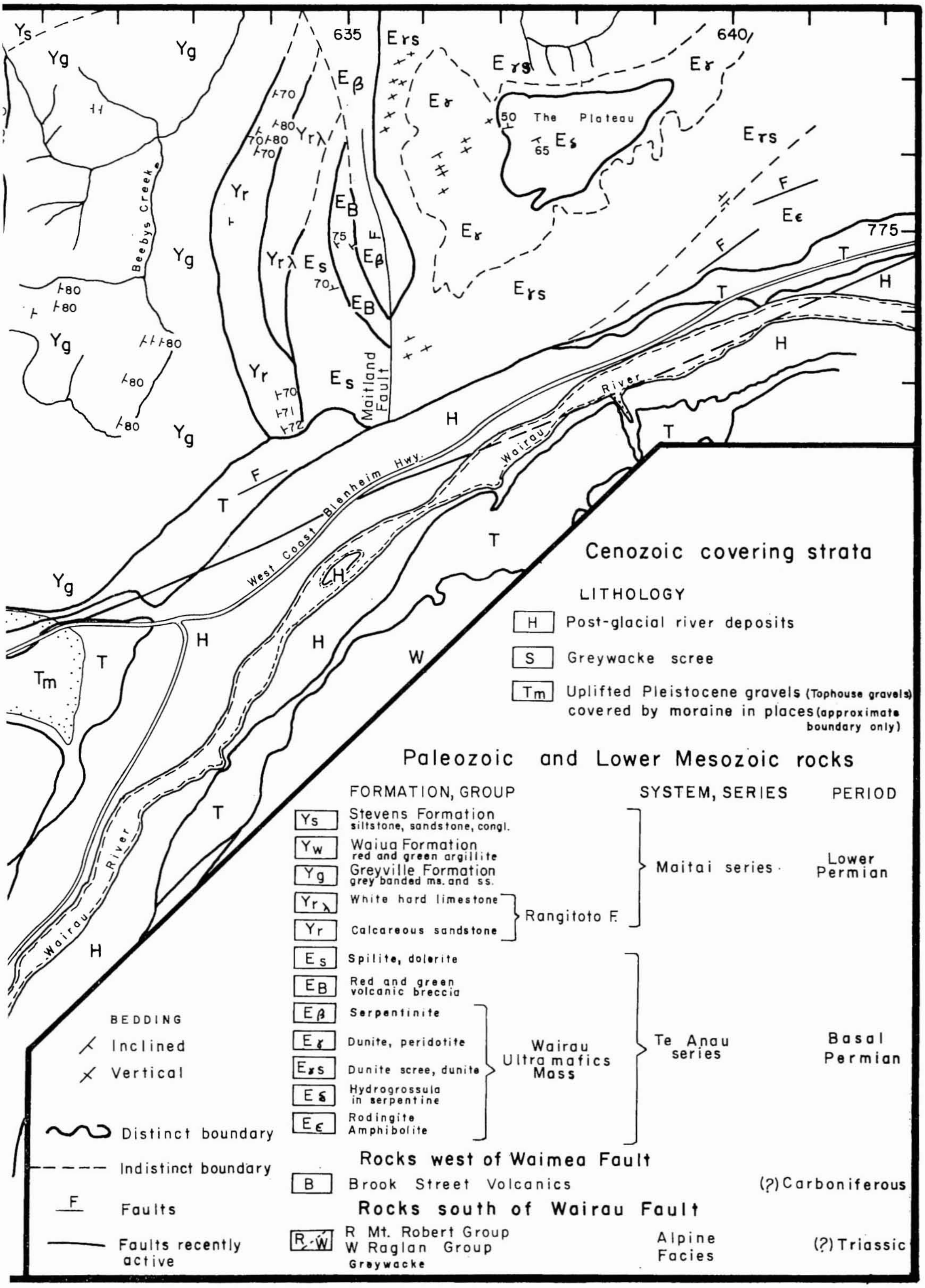


FIG. 2. Geology of the Tophouse district.



Cenozoic covering strata
LITHOLOGY
H Post-glacial river deposits
S Greywacke scree
Tm Uplifted Pleistocene gravels (Tophouse gravels) covered by moraine in places (approximate boundary only)
Paleozoic and Lower Mesozoic rocks
FORMATION, GROUP
SYSTEM, SERIES
PERIOD
Ys Stevens Formation siltstone, sandstone, congl.
Yw Waiua Formation red and green argillite
Yg Greyville Formation grey banded ms. and ss.
Yrλ White hard limestone
Yr Calcareous sandstone
Rangitoto F.
Maitai series
Lower Permian
Es Spilite, dolerite
EB Red and green volcanic breccia
Eβ Serpentinite
Eγ Dunite, peridotite
Eγs Dunite scree, dunite
Eδ Hydrogrossula in serpentine
Eε Rodingite Amphibolite
Wairau Ultra mafics Mass
Te Anau series
Basal Permian
Rocks west of Waimea Fault
B Brook Street Volcanics
(?) Carboniferous
Rocks south of Wairau Fault
R-W R Mt. Robert Group W Raglan Group Greywacke
Alpine Facies
(?) Triassic
BEDDING
Inclined
Vertical
Distinct boundary
Indistinct boundary
Faults
Faults recently active
The Plateau
Beebys Creek
Maitland Fault
West Coast Blenheim Hwy.
Wairau River
635
640
775

TABLE 1

STRATIGRAPHIC UNITS OF THE TOPHOUSE DISTRICT

SERIES AND AGE	FORMATION	MAP SYMBOL	LITHOLOGY	MAXIMUM THICKNESS IN FEET*
		S	mountain scree	
	Wairau surface	H	gravels, 10-ft terrace	100?
Holocene	Tophouse surface	T	fluvial gravels, silts, 200-ft terrace	300?
		Tm	glacial moraine	200?
		Major Unconformity		
Tertiary		t	terrestrial sediments	600?
		Major Unconformity		
	Stevens formation	YSa	tuffaceous siltstone (5,000 ft thick)	
		YSb	tuffaceous sandstone (6,000 ft thick)	11,000
Maitai Series, Upper Permian (?)	Waiua formation	Yw	green and purple banded mudstone and sandstone	2,500
	Greville formation	YG	grey banded argillite	9,000
	Rangitoto formation	YRλ	white limestone (2,000 ft thick)	
		YR	grey calcareous sandstone (1,800 ft thick)	3,800
		Cessation of Igneous Activity		
		Es	spilite, dolerite (extensively haematized)	4,000
		EB	haematized red and green volcanic breccia	1,000
Te Anau Series, Basal Permian		Stratigraphic Relationship Uncertain		
		Eβ	serpentinite	2,000
		Eγ	dunite, harzburgite, pyroxene peridotite	7,000
	Wairau ultramafic mass	Eγs	peridotite and peridotite scree	
		Eδ	serpentine containing hydrogrossular	500
		Eε	amphibolite, rodingite	5,000?
Rocks West of the Waimea Fault				
Te Anau Series, Carbonif-erous (?)	Brook Street volcanics	B	keratophyre, andesite, volcanic agglomerate, spilite	12,000
Rocks Southeast of the Wairau Fault				
Triassic	Alpine facies	R	Mount Robert group–greywacke, argillite	?
		W	Raglan group–greywacke, argillite	?

* As measured across outcrops in the Tophouse district.

TABLE 2

STRATIGRAPHIC CORRELATION BETWEEN PERMIAN ROCKS OF OTAGO* AND THE TOPHOUSE DISTRICT

SERIES AND AGE	FORMATION	EQUIVALENT TOPHOUSE FORMATION	LITHOLOGY	THICKNESS IN FEET
Maitai Series, Upper Permian?	Countess formation	Stevens formation	green, grey, maroon bedded sandstone, grit, conglomerate	11,000+
	Winton formation	Waiua formation	red- and green-banded argillite	1,000
	Tapara formation	Greville formation	grey-banded argillite	7,000
	Howden formation	Rangitoto formation	grey Maitaia bioclastic limestone, green sandstone, conglomerate	2,000
Cessation of igneous activity but no break in sedimentation				
Te Anau Series, Basal Permian	Livingstone volcanics		spilite, albite dolerite, albite gabbro, epidiorite, red and green breccia	3,000
	Red Mountain ultramafics	Wairau ultramafic mass	peridotite, dunite, serpentinite, gabbro, rodingite	?
	Stratigraphic relationship unknown			
	Eglinton volcanics		andesite, basalt, porphyrite, keratophyre, breccia, tuff	?

* From stratigraphic sequence determined by G. W. Grindley, 1958.

Volcanic conglomerate outcrops east of the Motupiko River and consists of rounded spilitic pebbles up to 3 cm in diameter, set in a chloritic groundmass (VUW 10658).[2] Phenocrysts of oligoclase feldspar are partially altered to epidote and seracite. The volcanic conglomerate is faulted against Stevens formation (Maitai series) by the Waimea Fault.

Te Anau Series

Grindley (1958:22) defined the Te Anau series in Otago as Upper Paleozoic (post-Devonian) sediments, volcanics, and intrusives deposited or erupted prior to the deposition of the Lower Permian Maitai limestone and not subsequently converted into schist or gneiss. In the Tophouse district, the Te Anau series is represented by the Wairau ultramafic mass and the Te Anau volcanics and underlies the Maitai limestone.

Wairau Ultramafic Mass

This mass is one of the two unserpentinized ultramafic masses of the Nelson ultramafic belt (see Fig. 1). A similar belt of ultramafic rocks extends southeastward from the Alpine Fault in Otago. The Red Mountain ultramafics of Otago (Grindley, 1958) are similar mineralogically to the Wairau ultramafic mass of South Nelson.

The rocks of this mass consist of peridotite and serpentinite. The largest exposure of peridotite is at the "Plateau," a peneplain surface 2,400 ft above the Wairau Valley. Northward of the Plateau, the peridotite becomes progressively dissected, resulting in craggy crests and steep, scree-covered slopes. While the Maitai rocks and Te Anau volcanics are covered by beech forest and scrub, the ultramafic rocks are covered by tussock grass only.

The Wairau ultramafic mass is faulted to the south, west, and possibly to the east. Air photographs show a strong lineation at 57° which is due to the alignment of dikes composed principally of pyroxenite. Banding, similar to that described by Hess (1960) in the Stillwater complex of Montana, is found along the whole western edge of the ultramafic mass. The coarse bands, consisting of pyroxenite and varying from 1 to 2 cm in width, are repeated hundreds of times within any outcrop. The dip in the area mapped is relatively low, from 20° to 40° E. The relationship of the banding to the general lineation referred to above is complex, and was not studied in detail.

The rocks of the Plateau include dunite, ortho- and clinopyroxene peridotite and harzburgite. These rocks are dark green and coarse-grained, and contain crystals up to 0.5 cm in diameter. Bands of resistant orthopyroxenite frequently stand out on the surface of the weathered rock. The pyroxene in the peridotite varies in type. Chromite is the sole accessory mineral. The dunite consists of large interlocking crystals of olivine, showing "strain" lamellae, and accessory chromite which occurs as elongate crystals, 2 mm in length. The density of the peridotites is constant at 3.30 ± 0.05 gm/cc for fresh unserpentinized samples and provides the density contrast of 0.6 gm/cc between the peridotites and New Zealand greywacke (the basement rock of 2.70 gm/cc density which is assumed to underlie the peridotite).

Serpentine containing hydrogrossular outcrops in the center of the Plateau and is coarse-grained, dark blue, and massive. Hydrogrossular is set within mesh serpentine in the rock, and olivine relicts as well as diopside fragments are abundant. The rock contains 10% granular magnetite. The gradational nature of the contact between the serpentinite and the surrounding peridotite suggests a metasomatic origin for the serpentinite.

Crushed serpentinite outcrops along a belt west of the Maitland Fault and forms the western boundary of the Wairau ultramafic mass. The Maitland Fault is the boundary between this serpentinite and the undeformed peridotite of the Plateau. The serpentinite is light green in color and breaks readily into green lensoid fragments 5–10 cm in diameter and 1–3 cm in thickness. Rocks near the Maitland Fault consist of antigorite serpentinite with slip fiber structure and are composed of large tabular crystals of antigorite with minor diopside. Tabular crystals of magnetite 2.5 mm in diameter form at least 10% of the rock by weight.

Amphibolite and rodingite occur as a wedge in the northeast corner of the area mapped (Fig.

[2] These numbers refer to rock catalogue numbers of specimens stored in the Geology Department, Victoria University of Wellington, New Zealand.

2) and appear to be faulted against the ultramafic rocks. Dikes of dense, white, fine-grained grossular diopside and chlorite rodingites (Grange, 1927) outcrop in stream beds of the Red Hills. The amphibolite which also outcrops in the same area is dark grey in the hand specimen and equigranular with aligned green hornblende crystals.

Upper Te Anau Volcanics

The breccia, spilite, and dolerite of the Tophouse district are similar to those in the belt of volcanics (Livingstone volcanics) between the Red Mountain ultramafics and the Howden formation of the Hollyford and Pyke Valleys in Otago (Table 2). The belt is cut off at the head of Pyke Valley by the Alpine Fault. In both Otago and South Nelson, the volcanics outcrop immediately above the serpentinite of the ultramafic belts and immediately below the Maitai limestone.

Distinctive red and green volcanic breccia outcrops immediately west of the Wairau ultramafic mass and is in direct contact with the serpentinites. The breccia consists of subangular fragments of spilite and dolerite pebbles, up to 15 cm in diameter but averaging 2 cm, surrounded by an igneous reaction rim. The pebbles are set in a fine-grained, dark-red hematitic base with vugs of calcite, and magnetite relicts. The breccia band is only 1,000 ft wide, dips steeply east, and strikes at 330°. To the east, the breccia is in direct contact with the serpentinites.

A belt of spilite, cut by dolerite dikes, lies between the breccia and the Maitai limestone. Directly beneath the limestone, the spilite is hematized and, in thin section (VUW 10667), shows vugs filled with spherulites of quartz and chlorite as well as phenocrysts of augite and serpentinized olivine set in a hematitic base. In the groundmass, acicular pyroxene crystals are aligned parallel to igneous flow structures. Magnetite, originally abundant, has been changed to hematite, giving the rock a red coloring. Away from the limestone contact, the spilites are green-grey in color. Texture is nonvesicular with a medium grain size.

Maitai Series (Group)

The lower formation of this series is the Maitai limestone in both the Tophouse district and in West Otago. The upper formation in these districts consists of volcanically derived sandstone. The four formations in the Maitai series in the Tophouse district may be correlated with those of Nelson and those of Otago (Grindley, 1958), which they match closely (Table 2). The oldest formation is Lower Permian in age (Wellman, 1952) and the youngest formation is Upper Permian. The Maitai formations have distinctive lithology and are easily mapped.

Rangitoto Formation

The formation is 3,800 ft thick and is well exposed along hill crests, west of the Red Hills. The base is marked by grey calcareous sandstone (30–40% calcite) with casts of *Atomodesma* impressions. The rocks show slaty cleavage and dip steeply east. The strike varies from 345° near the Wairau Fault to 025° two miles north. The calcareous sandstone grades up into coarse-grained massive limestone which in turn has a gradational contact with the Greville formation.

Greville Formation

The Greville formation consists wholly of laminated grey argillite and is exposed in a continuous sequence about 9,000 ft thick. Banding is regular, between 0.1 and 0.2 inches thick, and similar to that of varves. The darker bands consist of graded, coarse sandstone and lighter bands of fine siltstone. Slaty cleavage is well developed in parts of the formation. The strike of the rock is 015° and the dip ranges from 80° to 100°. Strike faulting is prominent and much of the drainage over the formation is aligned with the strike direction.

Laminations are graded, but much thinner than graded bands in greywacke. The resemblance between the laminations of the Greville argillites and those of varves shows up even more clearly under the microscope than in the hand specimen. It is likely that the bands represent annual layers.

Waiua Formation

The Waiua formation occurs as a faulted inlier near the Tophouse Hotel, where 2,500 ft of the rock is exposed. The rock consists of red- and green-banded argillite and sandstone with well-developed cleavage. The strike is 340° and the dip is nearly vertical. The banding in the argillite consists of tuffaceous sandstone, 3 mm thick, interbedded with argillaceous laminations 0.5–1.5 mm thick. In thin section, the green bands are seen to consist of sandstone with elongate grains of pyroxene, feldspar, and magnetite, set in a chloritic base. The red bands consist of argillite with a large proportion of hematite. Augen of hematite also occur in the sandstone bands. All the layers show graded bedding with laminations similar to those of the Greville formation. At the top of the formation, spacing of bands is irregular and thicker than in the Greville formation, massive semi-banded silts (VUW 10663) becoming prominent. Tuffaceous, banded sediments near the top of the formation consist of oligoclase feldspar, pyroxene, epidote, chlorite, and magnetite. All mineral grains show rounding. Green volcanic tuffs (VUW 10662), massive or vesicular in hand specimens, appear near the top of the Waiua formation. The change in coloration from the uniform grey of the Greville formation to the red and green of the Waiua formation is attributed to a mixture of tuffaceous material.

Stevens Formation

The lower part of Stevens formation consists predominantly of massive, green, volcanic sandstone and the upper part of tuffaceous siltstone. The contact between the upper and lower parts is abrupt and is probably a fault. The sandstone is 6,000 ft thick and dips vertically. The siltstone is 5,000 ft thick and dips 60° E at 340°. The sandstone is hard, lacks cleavage planes, is resistant to erosion, and forms prominent hill crests. It consists of semirounded mineral grains 0.03 mm in diameter, set in a chloritic matrix. Pyroxene and epidote are the chief components and the green color of the rock is due to alteration products of pyroxene. The siltstone is exposed in stream beds northeast of Tophouse Hotel. In thin section (VUW 10660), it appears to have an arkosic (oligoclase feldspar) composition and a chloritic matrix.

Alpine Greywacke

Lower Mesozoic greywacke and argillite is exposed southeast of the Wairau Fault in the Tophouse district. No detailed study was made of these rocks, but the following points were noted:

a.) Greywacke southwest of Mt. Robert tends to be schistose and denser than 2.67 gm/cc.

b.) The rocks of Mt. Robert and the St. Arnaud Range consist of 40% sandstone and 60% argillite. The argillite is dark blue in color, shows well-developed cleavage, and is calcareous with prominent calcite veins.

c.) The rocks of the Raglan Range consist of 10–20% argillite and 80–90% sandstone. The sandstone is light-colored and hard, and consists predominantly of rounded quartz grains.

d.) Intraformational calcitic and hematized spilites (VUW 10685) are interbedded in the greywacke of the Raglan Range and the St. Arnaud Range.

Quaternary Deposits

Most of the Quarternary alluvial deposits in the Tophouse district represent glacial advance during the Pleistocene glaciation.

The Tophouse gravels were deposited during the first recognized advance. The glaciers flowed from the site now occupied by Lake Rotoiti and, overriding the Brook Street volcanics, flowed north along the Motupiko Valley. A branch glacier probably flowed west over the Tophouse saddle and descended 2–5 miles down the Wairau Valley (Henderson, 1931:156). The lower limits of the glaciers were at 1,500–1,800 ft above the present sea level.

The Wairau Fault

The Wairau Fault is the major tectonic feature in the Tophouse district and is probably an eastward extension of the Alpine Fault (Fig. 1). The fault was examined in the field, but most of the information was obtained from air photographs and is shown in Table 3 (with nomenclature adapted from Wellman, 1953) and plotted on the geological map (Fig. 2).

The fault strikes eastward from Lake Rotoiti. Minor branch faults occur near Lake Rotoiti and along the northwest side of the Wairau Valley. Displaced and fault-aligned streams mark the fault trace on the north slopes of the St. Arnaud Range. The dip of the Wairau

TABLE 3

DATA ON THE POST-GLACIAL MOVEMENT OF THE WAIRAU FAULT FROM SPEARGRASS CREEK, MT. ROBERT TO WASH BRIDGE IN THE WAIRAU VALLEY

NATURE OF FAULT TRACE	LENGTH IN MILES	STRIKE DIR.	DIP		VERTICAL THROW		HORIZONTAL THROW		REFERENCE SURFACE
			AMT.	DIR.	THROWN SIDE	AMT. (FT)	NATURE	AMT. (FT)	
Stream bed	2.0	52°			SE				Speargrass Creek along fault zone (?)
*Scarp	0.5	66°			SE				scarp, partly concealed by scree at base of Mt. Robert
Scarp	0.4	68°	75°	NW	SE	40	C†	300	displaced shore line and glacial moraine
*Scarp	0.4	68°	75°	NW	SE	40	C	300	displaced shore line
Scarp	0.5	55°	90°	—	SE	50			displaced terrace
Scarp	0.1	55°?	90°	—	SE	20			displaced terrace
Rent	0.1	64°	90°	—	SE	20	C	330	displaced shore line
*Scarp	1.0	63°	80°	NW	SE				truncated spur
Scarp	1.0	64°	80°	NW	SE	60			stream
*Scarp	3.0	64°	80°	NW	SE	50			displaced mountain spur
Rent	3.0	64°	90°	—			C	700	displaced mountain spur and displaced stream
*Rent	0.5	64°	90°						fault line crosses highway
Rent	0.5	68°	90°	—	SE	30	C	300?	displaced terrace
Rent	0.2	67°	90°	—	SE	40	C	(?)	valley floor
Rent	0.3	67°	90°	—	SE	10	C	(?)	gravel terrace
Rent	0.2	65°	85°	NW	SE	80	—	—	displaced terrace
Rent	0.2	66°	90°	—	SE	—	—	—	displaced terrace
Rent	0.5	66°	90°	—	SE	10	—	—	recent movement (fault pond)
Scarp	1.0	42°	80°	SE	NW	200?	—	—	ancient fault trace
Scarplet	0.3	63°	85°	NW	SE	8	—	—	displaced terrace

* As determined by H. W. Wellman, 1952.
† C = Right lateral displacement.

Fault, as observed from surface scarps, appears to be vertical.

The ratio of the vertical to horizontal throw of the fault since the last glaciation is 1:10 (Table 4), and the rate of horizontal movement (including steady and sudden movement) is 0.36 inches per year. This rate is similar to the rate of 0.5 inches per year of dextral transcurrent creep recorded on the San Andreas Fault in California (Whitten et al., 1960).

TABLE 4
MEAN VALUES FOR VERTICAL AND HORIZONTAL THROW OF THE WAIRAU FAULT

LOCALITY	VERTICAL THROW (FT)	HORIZONTAL THROW (FT)
L. Rotoiti Peninsula	40	300
East shore L. Rotoiti	20	330
North flank St. Arnaud Range	50	250
Blenheim-West Coast Highway	30	300
Mean Values	35	300

GRAVITY

In the Tophouse district, intrusive and sedimentary rocks of the Maitai series, the Te Anau series, and the Brook Street volcanics are faulted against the homogenous Alpine greywacke by the Wairau Fault. In order to provide a simple geologic model for the gravity studies, the density of each formation has been assumed to be uniform throughout and in depth. Lithologic boundaries have been of prime importance in the interpretation of the gravity data.

The Worden gravity meter (W283) used in the survey has a scale range of 800 divisions, each division having a value of 0.0971 mgal. The base map has a scale of ½ mile to the inch and was constructed by standard methods from air photographs. Heights were read at each gravity station with three altimeters and frequent checks were made to points of known height. Also, daily variations in air pressure were determined with a barograph, located at the base station. Drift of the gravity meter was corrected by beginning and ending a set of readings for one day at the same station.

Because of the practical difficulty of making terrain corrections in areas of irregular topography, station sites were chosen within areas of smooth topography.

Gravimetric Corrections

All Bouguer gravity values are given in terms of Glenhope-Christchurch, i.e., the New Zealand Provisional System (Robertson and Reilly, 1960). The following corrections were made to the "observed" values:

(1) Latitude correction: The 1930 International Formula was used for determining latitude corrections. The increase in gravity to the south of the Tophouse district is 1.493 mgal per minute of latitude, or 1.298 mgal per mile.

(2) Elevation corrections:

(a) Free-air correction: This correction is constant and is 0.09406 mgal per foot of elevation.

(b) Bouguer correction: The attraction of the rock (taken as an infinite sheet in all directions) per foot of elevation between sea level and the gravity station is 0.01276 times the density of the rock. The density is assumed to be 2.67 gm/cc (the standard rock density), and variations from the assumed density have been allowed for in the interpretation of the gravity profiles.

(c) The combined correction: The Bouguer and elevation corrections are combined and a correction of 0.05999 mgal per foot of elevation was used for all the gravity stations.

(3) Terrain correction: Hammer's tables (Hammer, 1939) and a graticule were used to allow for irregular topography, topographic data being obtained from direct observations out to 558 ft from the gravity station and from N.Z.M.S. 1 contoured topographic maps (S26, S27, S33, S34) from 558 ft to 14 miles.

Errors in the Gravity Values

The position of the gravity stations is known to about 100 yards. Latitude errors do not exceed 0.05 mgal and hence are negligible. Heights are accurate to about 10 ft and produce errors of about 0.6 mgal. Errors arising from the correction of topography (judging from local irregularities) in the observed values do not exceed 0.2 mgal. Errors caused by the drift of the meter are negligible. The error in the Bouguer anomaly at any gravity station is not likely to exceed 1 mgal and is probably about 0.5 mgal.

Rock Densities

The density and magnetic susceptibility of representative rocks of the Tophouse district is given in Table 5.

In the Tophouse district, Maitai and Te Anau rocks are faulted against rocks of the Alpine facies whose measured densities range from 2.67 to 2.74 gm/cc and average 2.7 gm/cc. For the purposes of computation, the standard rock density for the Tophouse district is assumed to be 2.7 gm/cc, and differences from 2.7 are measured as the density contrast. Density differences between the standard rock and the overlying Maitai and Te Anau rocks are inferred to have produced the variations in the Bouguer anomalies (Fig. 3).

As the result of compaction and cementation, the porosities of most Maitai and Te Anau rocks are small. Only serpentinite and some tuffaceous rocks in the Maitai series have porosities greater than 5%. Fresh samples of Maitai and Te Anau rocks and of Alpine greywacke have porosities less than 2% and therefore particle densities have been adopted as the preferred density. Table 6 gives the particle densities of the Tophouse rocks and the density contrasts between these rocks and the local standard density of 2.7 gm/cc.

Gravity Anomalies of the Tophouse District

1. THE BOUGUER ANOMALIES: Dominant features of the Bouguer anomaly map (Fig. 3) are the northeast lineation of the anomaly contours and the decrease in gravity values southeast toward the regional low of the northern end of South Island. The uniform gravity trend on the southeast side of the Wairau Fault is a reflection of deep-seated variations in the thickness or composition of Alpine greywacke. Northwest of the Wairau Fault, the Brook Street high and the ultramafic high are superimposed upon the uniform trend. The anomalies are due to the fact that the rocks representing the Brook Street volcanics and the Wairau ultramafic mass are denser than the average basement rock.

2. THE REGIONAL BOUGUER ANOMALIES: These were used to remove the regional field from the Bouguer field and were plotted from values of gravity stations located on basement rock with a density of 2.67–2.7 gm/cc for the northern part of South Island (Fig. 3).

3. THE RESIDUAL ANOMALIES: Local grav-

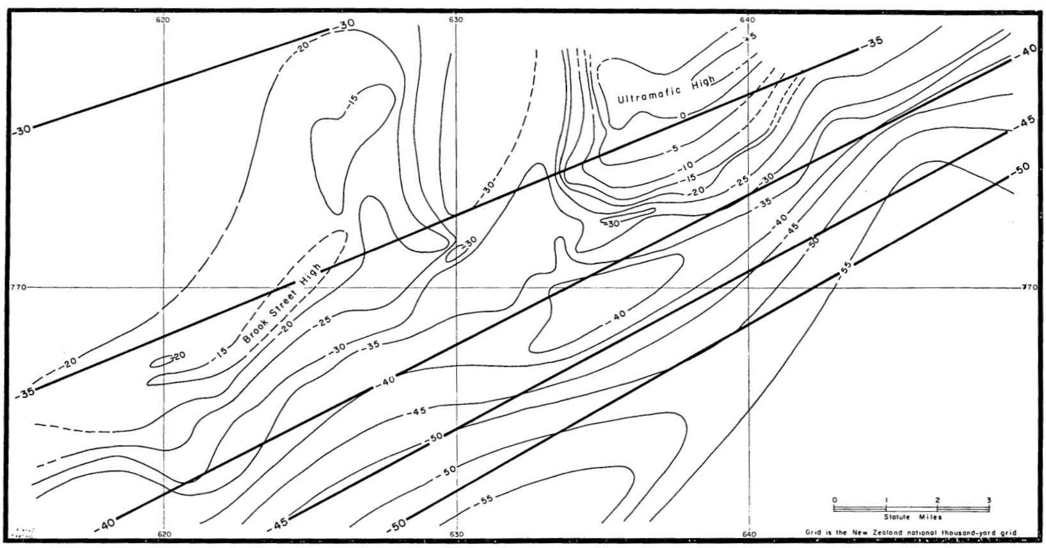


FIG. 3. Bouguer gravity anomaly pattern for the Tophouse district. Bold lines indicate regional Bouguer gravity trend. Contour interval at 5 mgal.

TABLE 5

DENSITIES AND MAGNETIC SUSCEPTIBILITIES OF REPRESENTATIVE ROCKS OF THE TOPHOUSE DISTRICT

DENSITY DRY	DENSITY WET	DENSITY PART.	*	ROCK TYPE	FORMATION	MAGNETIC SUSCEPT., CGS UNIT $\times 10^{-6}$
3.30	3.30	3.30	0	dunite	Wairau ultramafic mass	
3.30	3.30	3.30	0	dunite	Wairau ultramafic mass	
2.93	3.02	3.21	9	weathered dunite	Wairau ultramafic mass	
3.19	3.19	3.19	0	pyroxene peridotite	Wairau ultramafic mass	206
3.20	3.20	3.21	0	pyroxene peridotite	Wairau ultramafic mass	247
3.33	3.33	3.34	0	dunite	Wairau ultramafic mass	
3.34	3.34	3.35	0	dunite	Wairau ultramafic mass	
3.32	3.32	3.32	0	harzburgite	Wairau ultramafic mass	204
3.11	3.13	3.18	2	harzburgite	Wairau ultramafic mass	
3.24	3.25	3.27	1	weathered dunite	Wairau ultramafic mass	
3.26	3.27	3.30	1	pyroxene peridotite	Wairau ultramafic mass	220
3.24	3.24	3.25	0	pyroxene peridotite	Wairau ultramafic mass	
2.68	2.68	2.68	0	hard serpentinite	Wairau ultramafic mass	
2.83	2.84	2.84	1	hard serpentinite	Wairau ultramafic mass	2840
2.56	2.58	2.61	2	hard serpentinite	Wairau ultramafic mass	1960
2.66	2.66	2.67	0	hard serpentinite	Wairau ultramafic mass	1300
2.92	2.94	2.97	2	serpentinized dunite	Wairau ultramafic mass	
2.57	2.60	2.66	3	soft serpentinite	Wairau ultramafic mass	940
2.22	2.34	2.53	12	soft serpentinite	Wairau ultramafic mass	1435
2.88	2.88	2.89	0	amphibolite	Wairau ultramafic mass	
2.88	2.89	2.91	1	amphibolite	Wairau ultramafic mass	
2.91	2.92	2.93	1	amphibolite	Wairau ultramafic mass	
2.87	2.89	2.92	2	amphibolite	Wairau ultramafic mass	430
2.92	2.93	2.95	1	red volcanic breccia	Wairau ultramafic mass	
2.81	2.84	2.90	3	spilite		
2.86	2.87	2.91	1	spilite		125
2.93	2.94	2.95	1	dolerite		66
2.79	2.80	2.82	1	red and green schist		120
2.76	2.78	2.80	2	green schist		
2.99	2.99	3.00	0	spilite	Brook Street volcanics	
2.89	2.90	2.92	1	spilite	Brook Street volcanics	
2.90	2.90	2.91	0	spilite	Brook Street volcanics	1000
2.78	2.80	2.84	2	volcanic agglomerate	Brook Street volcanics	93
2.61	2.64	2.69	3	volcanic tuff	Brook Street volcanics	38
2.68	2.69	2.70	1	hard limestone	Rangitoto formation	0
2.67	2.68	2.69	1	grey calcareous sandstone	Rangitoto formation	0
2.60	2.63	2.67	3	calcareous sandstone	Rangitoto formation	0
2.64	2.67	2.71	3	grey slate	Greville formation	22
2.63	2.68	2.75	5	grey slate	Greville formation	20
2.68	2.71	2.77	3	grey slate	Greville formation	20
2.74	2.77	2.82	3	red and green slate	Waiua formation	
2.34	2.47	2.69	13	tuff	Waiua formation	40
2.71	2.73	2.75	2	metasomatized volcanics	Waiua formation	58
2.82	2.85	2.90	3	volcanic sandstone	Stevens formation	230
2.92	2.95	2.94	1	volcanic sandstone	Stevens formation	50
2.70	2.72	2.77	2	volcanic siltstone	Stevens formation	
2.67	2.71	2.79	4	volcanic siltstone	Stevens formation	50
2.61	2.63	2.66	2	greywacke sandstone	Alpine facies (Raglan series)?	
2.62	2.62	2.64	0	greywacke sandstone	Alpine facies (Raglan series)?	

TABLE 5 (continued)

DENSITY DRY	DENSITY WET	DENSITY PART.	*	ROCK TYPE	FORMATION	MAGNETIC SUSCEPT., CGS UNIT $\times 10^{-6}$
2.44	2.51	2.62	7	greywacke sandstone	Alpine facies (Raglan series)?	34
2.61	2.63	2.66	2	greywacke sandstone	Alpine facies (Raglan series)?	
2.67	2.69	2.72	2	haematitic chert	Alpine facies (Raglan series)?	39
2.67	2.68	2.69	1	greywacke sandstone	Alpine facies **	
2.66	2.67	2.67	1	greywacke sandstone	Alpine facies **	30
2.63	2.65	2.67	2	greywacke sandstone	Alpine facies **	120
2.74	2.75	2.76	1	argillite	Alpine facies **	74
2.75	2.76	2.79	1	argillite	Alpine facies **	
2.74	2.75	2.77	1	argillite	Alpine facies **	
2.72	2.72	2.73	0	argillite	Alpine facies **	
2.66	2.68	2.70	2	greywacke conglomerate	Alpine facies **	40
2.67	2.68	2.69	1	greywacke sandstone	Alpine facies	49
2.64	2.65	2.67	1	greywacke sandstone	Alpine facies	28
2.82	2.85	2.90	3	calcareous spilite	Alpine facies	360

* Porosity (%).
** Alpine facies (Mt. Robert series).

TABLE 6

PREFERRED DENSITIES OF ROCKS USED IN GRAVITY REDUCTIONS OF THE TOPHOUSE DISTRICT

ROCK	DENSITY (GM/CC)	DENSITY CONTRAST WITH STANDARD ROCK (GM/CC)
Alpine greywacke	2.70	0.00
Pleistocene gravels	2.25	—0.45
Stevens form. siltstone	2.78	0.08
Stevens form. sandstone	2.92	0.22
Waiua form. banded slate	2.82	0.12
Greville form. argillite	2.74	0.04
Rangitoto form. limestone	2.70	0.00
Te Anau ser. dolerite	2.95	0.25
Te Anau ser. spilite	2.90	0.20
Te Anau ser. red and green volcanic breccia	2.95	0.25
Serpentinite	2.65	—0.05
Dunite, pyroxenite	3.30	0.50
Brook Street volcanics (spilite)	2.94	0.24

ity anomalies show up more clearly in the residual gravity map (Fig. 4) and are quantitatively related to the surface geology.

The axis of the Brook Street high extends 1 mile west of Tophouse and gravity values decrease in that direction. Anomaly contours below the value of + 16 mgal appear to extend in a southwest direction from Lake Rotoiti. The axis of the Brook Street high has a north-to-south trend above Tophouse. This direction is parallel to the strike of the Brook Street volcanics, the Maitai series, and the strike of the Waimea Fault. The maximum positive value of 22 mgal is considered to indicate the position

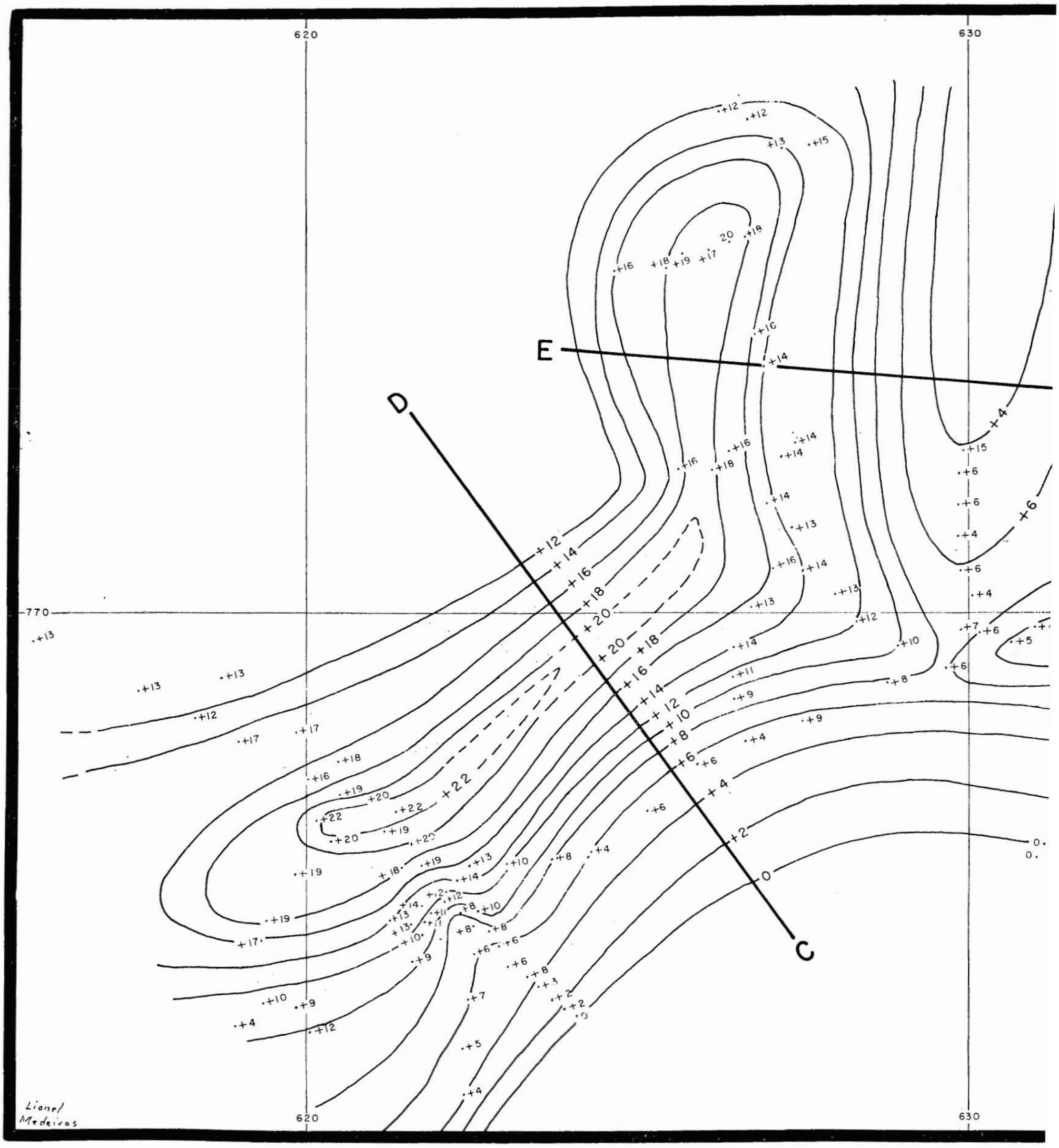
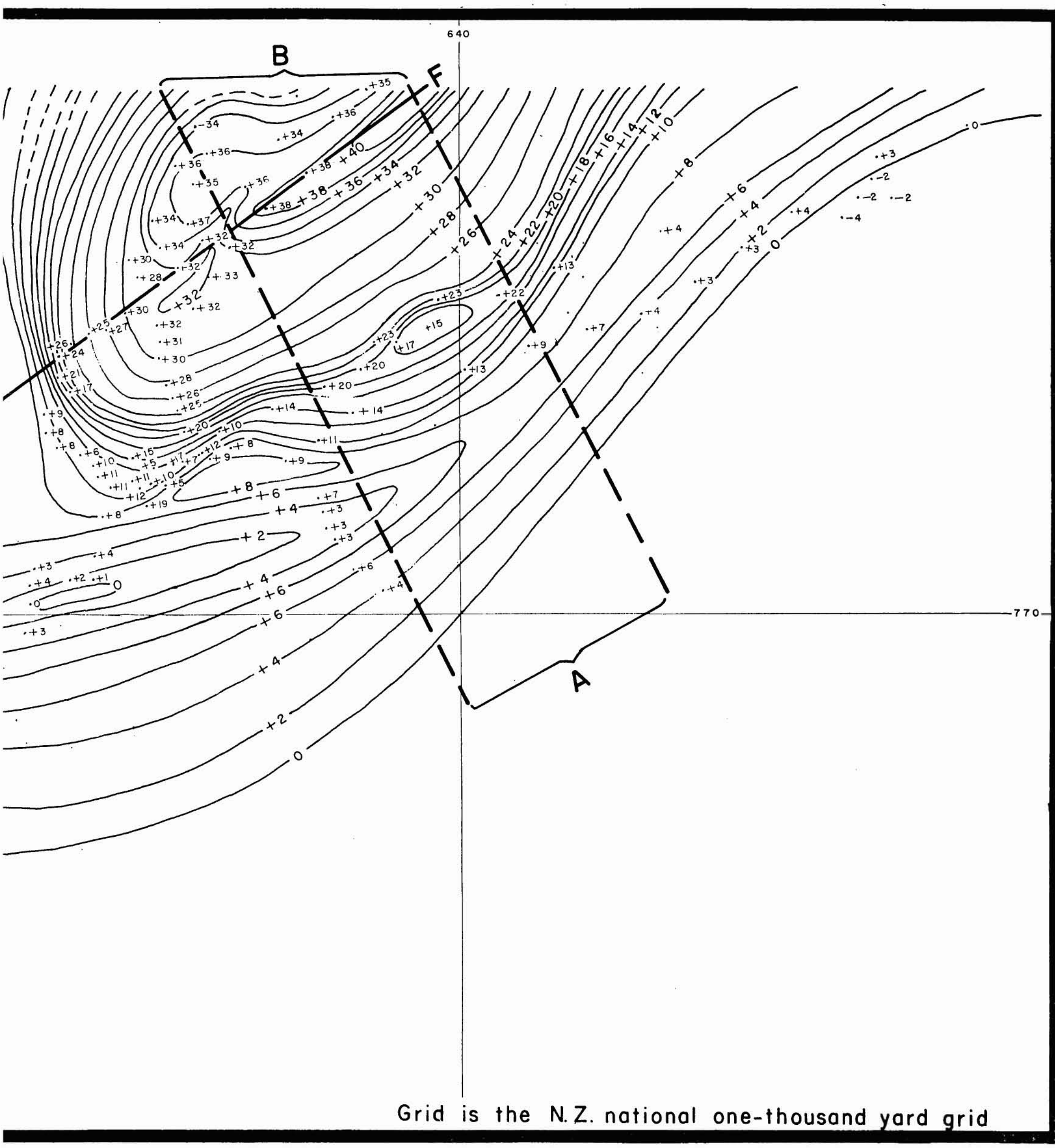


FIG. 4. Residual gravity anomaly pattern for the Tophouse district. Contour interval at 2 mgal. Lines A–B, C–D, and E–F show location of gravity profiles (see Figs. 5, 6, and 7, respectively).


640
B
F
A
770
Grid is the N.Z. national one-thousand yard grid

of the maximum thickness of the volcanics below sea level. The Brook Street volcanics are flanked to the west by the Rotoroa igneous complex and to the east by the Maitai series. South of Tophouse Hotel, however, the axis of the Brook Street high swings around to strike parallel to the Wairau Fault. The change in the axial trend of the gravity anomaly from south to southwest is attributed to the bending and dragging of the Brook Street volcanics by transcurrent movement along the right lateral Wairau Fault.

The ultramafic high reaches a maximum positive value of 40 mgal. Along the margin, the gravity gradient is steep and it is inferred that the contacts surrounding the Red Hill ultramafic mass are also steep. Small gravity lows near the crest of the anomaly are attributed to shallow inclusions of serpentinite. The serpentinite along Maitland Fault is not reflected by a gravity low and is therefore considered to be underlain at a depth of a few hundred feet by peridotite.

The small negative anomaly of 4 mgal at the eastern bay of Lake Rotoiti is inferred to be caused by about 600 ft of glacial outwash gravel and silt. Another small negative anomaly with a maximum negative value of about 7 mgal is situated along the Wairau Valley 1 mile east of the Tophouse saddle and is inferred to be caused by about 1,000 ft of alluvium. No negative anomalies were observed over the Tophouse saddle, where the alluvium is about 300 ft thick.

Structure of the Maitai and Te Anau Rocks

1. GRAVITY ANOMALY PROFILES: Two regular geological features are represented by the gravity contours. One is the contact between the Rotoroa igneous complex and the Brook Street volcanics at depth, and the other is the contact between the peridotite of the Wairau ultramafic mass and Alpine greywacke at the Wairau Fault. These two structures have been studied in detail. The three gravity profiles are drawn perpendicu-

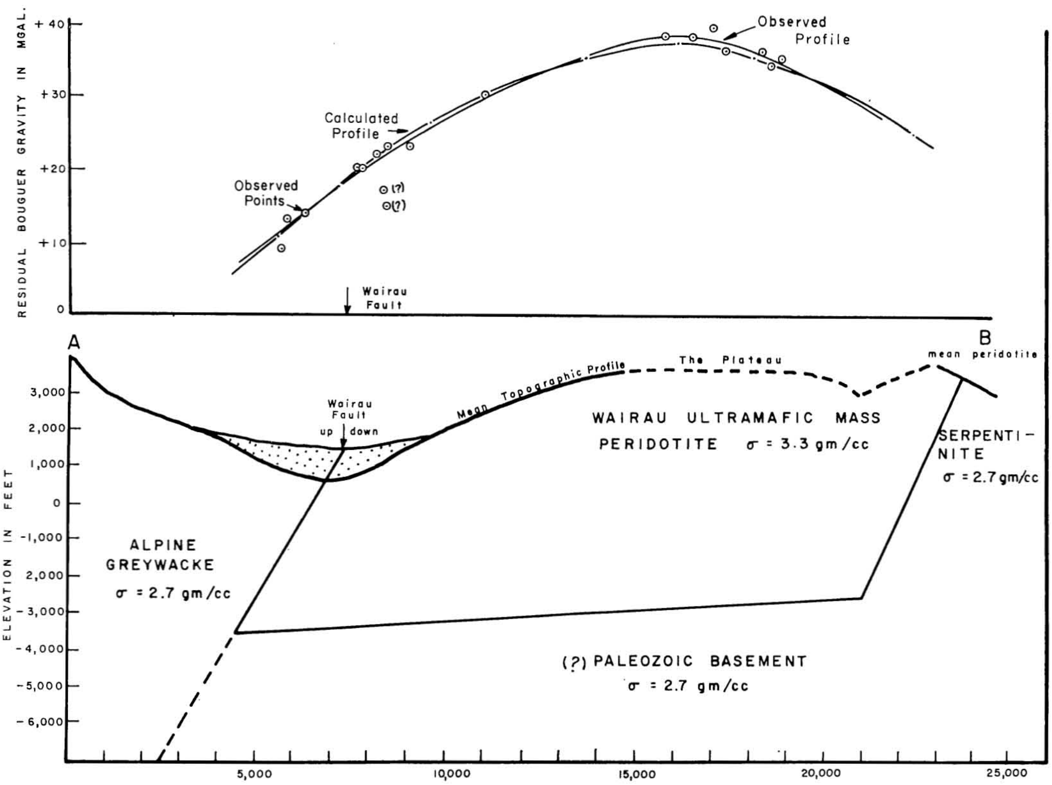


FIG. 5. Gravity profile A–B across the Wairau ultramafic mass.

lar to the residual gravity anomaly contours and are shown in Figure 4.

Profile A–B (Fig. 5): Alpine Greywacke–Wairau Fault–Wairau Ultramafic Mass. In order to eliminate local irregularities, the average gravity values over a 2-mile-wide belt were taken normal to the anomaly contours as shown by profile A–B. Two of the observed values, marked by question marks in Figure 5, fall well below the others and have been neglected. A model with a theoretical curve which fits the observed curve to within 0.1 mgal is shaded. This model represents a simplified geological cross section across the Wairau ultramafic mass. A northeast dip of 67° for the Wairau Fault provides the best gravimetric solution and is probably correct to within 15°.

Profile C–D (Fig. 6): Brook Street Volcanics–Waimea Fault–Wairau Fault. Gravel and moraine obscure the contact between the Brook Street volcanics and the Rotoroa igneous complex. The western contact of the volcanics is at the Waimea Fault and gravimetric studies show that the axis of maximum thickness of the volcanics lies 3 miles west of the fault outcrop.

The calculated gravity profile for the geological model (shaded) fits the observed curve to within 0.5 mgal along the margins of the curve. The peak of the calculated profile falls below the peak of the observed profile by 3 mgal. The differences can be resolved only by assuming that the density of the Brook Street volcanics is not uniform throughout and it is likely that denser rocks underlie the surface rocks.

Profile E–F (Fig. 7): Rotoroa Igneous Complex–Brook Street Volcanics–Maitai Series–Wairau Ultramafic Mass. The profile is perpendicular to the regional strike of the rocks and extends east from the Brook Street volcanics to the Maitai series and then northeast to the Wairau ultramafic mass. Observed values are irregular over the Wairau ultramafic mass and values have been averaged over a width of 2 miles along the profile.

The calculated gravity curve for the assumed

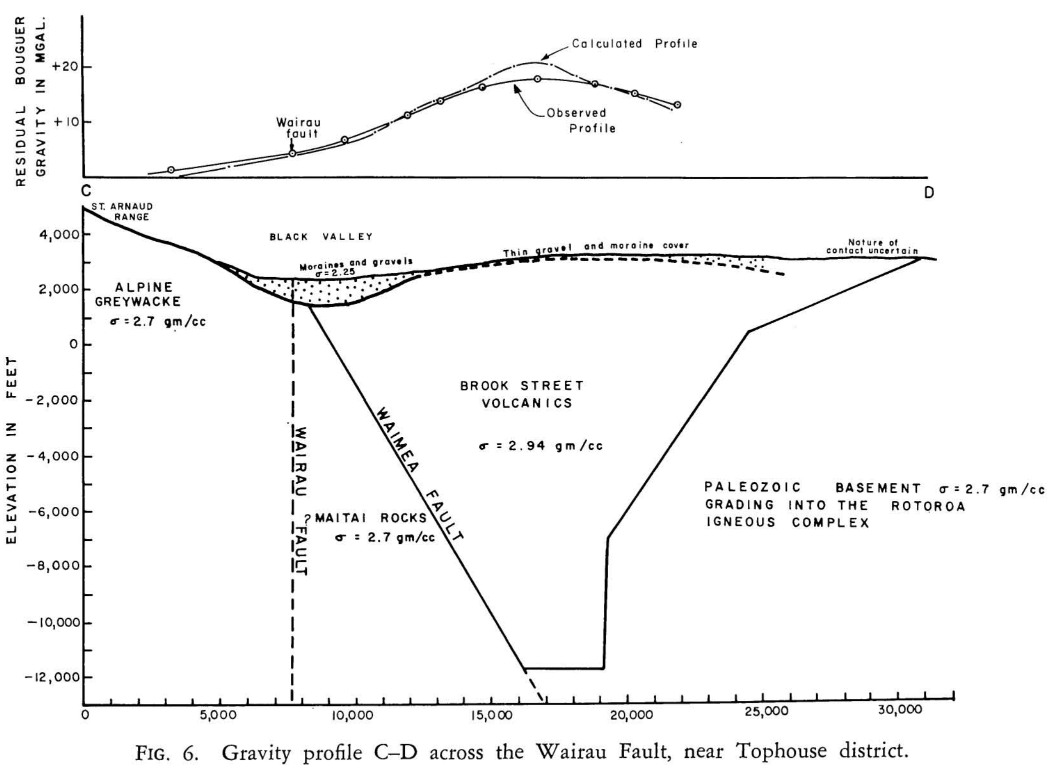


FIG. 6. Gravity profile C–D across the Wairau Fault, near Tophouse district.

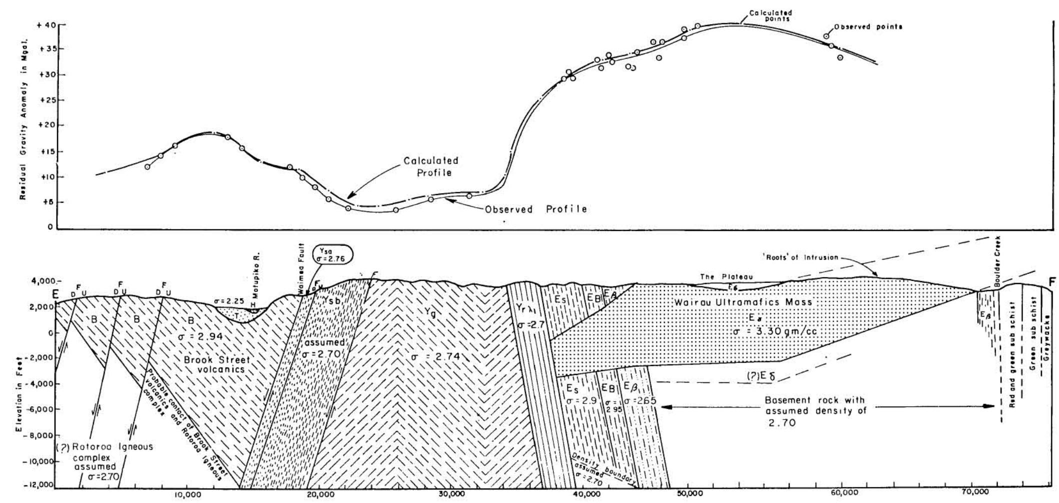


FIG. 7. Gravity profile E–F across the Brook Street volcanics to the Wairau ultramafic mass.

densities fits the observed curve to within 2 mgal in all places. The most surprising feature of the profile is the 90° angle between the dips of the Maitai series–Te Anau volcanics and the attitude of the calculated base of the Wairau ultramafic mass.

2. DISCUSSION OF GEOLOGICAL STRUCTURE AS INTERPRETED FROM GRAVITY RESULTS: The Brook Street volcanics lie between the Waimea Fault to the east and the Rotoroa igneous complex to the west. The Waimea Fault has been observed to dip steeply west and the Brook Street volcanics have been observed to dip between 50° and 60° east. Interpretation of the gravity profiles shows that the Waimea Fault dips 70° west and that the maximum stratigraphic thickness of the Brook Street volcanics in the Tophouse district is about 13,000 ft, reaching a maximum vertical thickness of 12,000 ft near the Waimea Fault. The Brook Street volcanics are probably underlain by rocks of the Rotoroa igneous complex, for which a density of 2.7 gm/cc has been assumed. The nature of this contact is unknown. A series of faults west of the Waimea Fault have been observed from air photographs and appear to dip steeply west.

Rocks of the Maitai series range in density from 2.70 gm/cc (Rangitoto formation) to 2.92 gm/cc (Stevens formation sandstone). However, no significant gravity anomalies were observed over these rocks, and it is inferred that the denser rock members do not extend to depth as expected from surface observations and are probably underlain by Maitai rocks with a mean density of 2.7 gm/cc at depth.

Te Anau spilite, dolerite, and red and green volcanic breccia, with a mean density of 2.9 gm/cc, lie east of the Maitai series. Gravity results suggest that these relatively dense rocks are underlain at 12,000 ft below sea level by rocks of standard density. The nature of the contact is uncertain.

Geological interpretation of the positive gravity anomaly associated with the Wairau ultramafic mass has been based on two profiles (Figs. 5 and 7) constructed from average values over a width of 2 miles. Gravity values indicate that the peridotite is about 7,000 ft thick, with a maximum thickness below the Plateau (Fig. 7). South of the Plateau, the peridotite is faulted by the Wairau Fault against Alpine greywacke. At the fault contact the average dip from the surface down to the base of the peridotite appears to be 67° southeast with an error of about ± 15°. The Wairau ultramafic mass does not extend southward beyond the Wairau Fault.

A subsurface western extension of the Wairau ultramafic mass below the Te Anau volcanics is necessary in order to explain the large positive gravity values observed over the volcanics. The peridotite apparently intrudes the upper

Te Anau volcanics, probably up to the base of the Maitai limestone. The peridotite, therefore, is younger than the volcanics and older than the Rangitoto (Maitai) limestone. The present shape of the ultramafic mass is that of a horizontal sheet with near-horizontal structures such as low-angle dipping bands. Hence, if the original dip of the Te Anau volcanics and the Maitai series was horizontal, the original dip of the Wairau ultramafic mass was probably vertical. This suggests a vertical mode of emplacement for the Wairu ultramafic mass. The inferred relationship (Grindley, 1958: 35) can be seen by turning Figure 7 sideways, so that the Maitai series are at the top. The peridotite of the ultramafic mass could have been intruded vertically after the extrusion of serpentinite lavas, the red and green volcanic breccia, and the spilite. After the intrusion of the peridotite, a period of erosion was followed by the deposition of the Rangitoto limestone and the rest of the Maitai series. Later, regional tilting and folding exposed the "roots" (Fig. 7) of the ultramafic mass. The roots were subsequently destroyed by erosion.

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